

# A NEW CANDIDATE FOR THE DARK MATTER

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## Abstract

It is shown that if there are two distinct phase transition temperatures to the hadronic phase ( as is currently favoured), then QCD demands a condensation to a weakly interacting massive glueball. This glueball then becomes a natural candidate for the cosmological dark matter. Note that this does not involve any exotic extensions beyond the Standard Model of particle physics. In this revised version at the end of the paper I have added a new section called ADDENDUM which gives new arguments as to how this very heavy glueball can be stable and hence be a dark matter candidate.

Among the few facts of cosmology is the existence of dark matter (DM) [1]. In recent years it has become one of the most active areas of research in physics and astronomy [2]. There is no dearth of DM candidate, both baryonic and non-baryonic [3, 4]. The existence of none of these has been satisfactorily demonstrated as of now [1, 2, 3, 4]. It may be noted that most of these candidates are based on particle physics models which are some kind of extensions beyond the Standard Model (SM) (of particle physics). All these are highly speculative as these themselves have not been observed anywhere else [5].

It is a common belief that the SM of particle physics based on the group  $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$  is not rich enough to justifiably accommodate the full complexity of the DM problem. (And hence the necessity to go beyond the SM, as stated above). In this paper I shall however show that actually there is new candidate of DM - which is glueball, whose existence is predicted within the framework of the SM itself.

Because of the non-abelian character of the  $SU(3)_c$  (on which the Quantum Chromodynamics (QCD) is based) the gluons self interact. This interaction does not require the existence of matter particles (i.e quarks etc). Hence in QCD on very general grounds one expects the existence of the bound state of these gluons, the so called glueballs. Much work has been done on these glueballs both theoretically and experimentally (see [6] for references) but no definitive glueball candidate has been identified so far.

The currently very active ultrarelativistic heavy-ion collision programme is being pursued with the hope of attaining the quark - gluon plasma (QGP) phase of the hadronic matter. Earlier it was expected that the hadron to QGP phase transition would take place at a single temperature  $T_c \sim 150-200$  MeV [6]. Working in pure  $SU(3)_c$  theory (where no quarks were present) it was shown that, free massless gluons which existed above  $T_c$  condense through first order phase transition to a weakly interacting gas of massive glueballs below  $T_c$  [7]. There has been discussion as to whether the transition is first order or second order. Here for the sake of simplicity we take the view that this phase transition is first order [8].

Recently it has been becoming popular to talk of two distinct phase transition temperatures in QGP [9]. For example it has been argued that the equilibrium of gluons takes place in time  $\tau_g \sim \frac{1}{2}$  fm/c while the production and equilibration of quarks takes place in  $\tau_q \sim 2$  fm/c. Hence one has a hotter pure gluon plasma. It has been shown [9] that the pure gluon plasma

transition temperature  $T_g \sim 400$  MeV and for the quark phase  $T_q \sim 250$  MeV .

We accept this two stage transition temperatures for QGP and turn the argument around. In the big - bang scenario as the universe cools it goes through various phase transitions [1, 2, 3, 4, 5]. After the Electro - Weak symmetry is broken at temperature  $\sim 200$  GeV , the particle content is  $\gamma$ ,  $\nu_e$ ,  $\bar{\nu}_e$ ,  $\nu_\mu$ ,  $\bar{\nu}_\mu$ ,  $\nu_\tau$ ,  $\bar{\nu}_\tau$ ,  $e^+$ ,  $e^-$ ,  $\mu^+$ ,  $\mu^-$ ,  $u$ ,  $\bar{u}$ ,  $d$ ,  $\bar{d}$ , and gluons. This remains so until the temperature cools down to  $\sim 400$  MeV . At this instant the first hadronic phase transition takes place. Most ( or all ) gluons undergo first order phase transition and condense to massive weakly interacting glueballs. there is a freeze out and they decouple with the rest of the particles. There are very few free gluons present immediately after this phase transition. However very soon due to the reaction  $qq \rightarrow gg$  the quarks " dress " themselves up. By the time the temperature drops to  $\sim 250$  MeV, there are enough quarks and gluons present to lead to the normal QGP phase transition to the standard hadronic matter.

The weakly interacting massive glueballs become a relic species in the universe. In the lowest order the glueball does not couple to photons and hence would be an ideal candidate for the dark matter. Hence there exists within the framework of SM an object - the glueball which here is proposed to be the new DM candidate.

To get an estimate of the mass of the glueball let us assume that when it decouples it is non relativistic :

$$T_g \ll m_g$$

Hence we obtain a conserved number N [4]

$$N = \frac{n}{s} = 0.145 \left( \frac{g}{g_*} \right) \left( \frac{m_g}{T_g} \right) \exp \left( -\frac{m_g}{T_g} \right) \quad (1)$$

Where  $g_*$  is the number of species in equilibrium when the glueball decouples. Taking  $\rho_c$  to be  $1.06 \times 10^4 h^2 eV - cm^{-3}$  and imposing the constraint

$$(\Omega h^2)_{glueball} \leq 1 \quad (2)$$

If  $T_g \sim 400$  MeV [9] then we find that  $m_g \geq 44.6$  GeV. So our estimate is that the glueball constituting the DM of the universe is very heavy  $\geq 44.6$  GeV.

All the estimates of the glueball studied theoretically [6, 7] have been of the order of 1 GeV for the lightest  $0^{++}$  glueball. In all the extensive searches for the glueball none has yet been detected. It's possible that we have not really understood the complete ( mainly non-perturbative ) dynamics of QCD [6, 7]. Nevertheless the DM candidate glueball  $m_g \geq 44.6$  GeV found here can not be the light glueball suggested by others. Clearly work has to be done to understand how one can obtain such a massive glueball. Is it some long lived metastable state arising due to the complex dynamics of QCD ? What kind of collectivity does it involve and what kind of phase transition in QCD will give this ?

In summary, if we accept the currently popular two distinct hadron phase transition temperatures in QGP [9], then pure glueball condensation is naturally demanded by QCD. This then becomes a natural candidate for DM. This glueball is necessarily very massive too. The interesting point is that this dark matter candidate is arising from the structure of the currently most successful model of particle physics -the Standard Model and does not involve any exotic extensions beyond it.

## ADDENDUM

So what is this heavy glueball and why is it so stable? Note that we used the pure gluon plasma transition temperature  $T_g \sim 400$  MeV and for the quark phase  $T_q \sim 200$  MeV. We find that a heavy glueball ( $m_g \geq 44.6$  GeV) arises due to the phase transition at  $\sim 400$  MeV and the rest of the hadron matter is created at  $\sim 200$  MeV. There is no a priori reason why the QCD phase transitions at these two distinct temperatures have the same nature. The nature of the QCD phase transition at 250 MeV, which leads to the standard hadrons has been well studied in recent years and we can take it as rather well understood [7]. So we do not mess around with this. But what do we really know of the QCD phase transition at  $\sim 400$  MeV? Is it not possible that this phase transition is slightly different from the other one? Hypothesising this way we can right away understand the nature of the heavy glueball which has been proposed as a dark matter candidate.

Let us assume that the QCD phase transition at  $T_g \sim 400$  MeV leads to the version of QCD as discussed by De Rujula, Giles and Jaffe, Phys. Rev. **D17** (1978) 285. Their framework is renormalizable spontaneously broken version of QCD. Color SU(3) remains an exact global symmetry. The successful phenomenology of color-singlet hadrons is altered very little and at the presently available energies the model is not inconsistent with any experimental information. There is atleast one stable hadron for every representation of color SU(3). Note that in our picture the phase transition at  $T_g \sim 400$  MeV leads to only glueball condensation (remember quark condensation takes place later at  $T_q \sim 250$  MeV as per standard unbroken QCD). Hence the glueballs that arise belong to the octet representation of SU(3). They are heavy and stable. This is the glueball dark matter candidate discussed above.

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